Conf-911043--3

PNL-SA--20032

DE92 004503

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October 1991

Presented at the
30th Hanford Symposium on Health
and the Environment
October 29 - November 1, 1991
Richland, Washinngton

Work supported by
the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

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ABSTRACT

Sites previously used for disposal of radioactive and hazardous chemical materials have resulted in situations that pose a potential threat to humans from inadvertent intrusion. An example generic scenario analysis was developed to demonstrate the evaluation of potential exposure to either cleanup workers or members of the public who intrude into buried waste containing both radioactive and hazardous chemical contaminants. The example scenarios consist of a collection of exposure routes (or pathways) with specific modeling assumptions for well-drilling and for excavation to construct buildings. These scenarios are used to describe conceptually some potential patterns of activity by non-protected human beings during intrusion into mixed-waste disposal sites.

The dose from exposure to radioactive materials is calculated using the GENII software system and converted to risk by using factors from ICRP Publication 60. The hazard assessment for nonradioactive materials is performed using recent guidelines from the U.S. Environmental Protection Agency (EPA). The example results are in the form of cancer risk for carcinogens and radiation exposure. The results indicate that radiation doses potentially received during excavation will exceed those during well drilling primarily because of the increased duration of exposure involved in excavation. Applying the results of these scenarios to an occupational setting may provide an upper bound of the risk resulting from one exposure event.

INTRODUCTION

The U.S. Department of Energy (DOE) controls disposal sites for low-level radioactive waste and mixed radioactive and hazardous materials resulting from a number of past DOE operations. Current DOE guidance calls for management of past waste sites in a manner that will 1) protect the health and safety of the public, 2) preserve the environment of the sites, and 3) ensure that no remedial actions will be necessary after termination of operations.[1] To evaluate potential impacts on public health and safety, DOE conducts performance assessments in a modeling process that uses the best available data on engineering, waste form, inventory, and environmental characteristics. The modeling results are prospective; that is, they provide an evaluation of future performance of a site or disposal system. An evaluation of human intrusion is included in these assessments.

Performance assessment methods typically focus on estimation of the radiation dose to an individual from radioactive materials present in disposal sites. When hazardous materials are present, an additional hazard assessment is necessary to evaluate the potential cancer risk from carcinogens or hazards from non-carcinogens. Guidance for non-radioactive constituents is provided in Risk Assessment Guidance for Superfund, Volume I: Human Health Evaluation Manual.[2] The risk of health-effects from non-carcinogens are assessed using a reference dose and hazard index. Because the risks from non-carcinogens are much less limiting than the risks from carcinogens, the risk from carcinogenic and radioactive materials in mixed waste is emphasized here. In addition,

the cancer risk from carcinogenic chemicals can be compared with the cancer risk from radiation dose. This paper provides an overview of intruder scenarios and risk assessment methods; it also provides a sample generic demonstration of a modeling evaluation of the potential risks associated with intrusion into mixed waste disposal sites when no protective measures are taken.

SCENARIOS

Intruder scenarios are used to model the potential activities of individuals who, unknowingly, disrupt buried waste sites. These individuals may in fact be members of the cleanup work force who, during site characterization, environmental data collection, or construction activities, may inadvertently encounter buried waste. A variety of intruder scenarios have been identified in the literature for low-level radioactive waste.[3] Two common scenarios that apply to most sites include water well-drilling and excavation or construction. Descriptions of these scenarios and some probable exposure pathways follow.

Well Drilling

The well-drilling scenario may apply to a variety of wastes and to depths greater than 5 m at any time after disposal. The drilling scenario involves penetrating the waste layer and bringing up a drill-core volume to the land surface. The volume brought to the surface during drilling is a function of the drill-core diameter and the thickness of the waste disposal zone. Exposure pathways considered in

the well-drilling scenario include inhalation of contaminated dust or volatile chemicals, external radiation exposure, dermal exposure to chemicals, and incidental ingestion of soil.

Excavation

The excavation or construction scenario assumes that the intruder is a worker who contacts disposed waste while excavating to characterize or clean up a site or to build a structure after release of a site. The quantity and accessibility of the disturbed waste depends on the depth and thickness of the buried waste, the physical or chemical waste form, and the method of excavation used. This paper assumes that the excavator has removed the clean overburden and is working in an area surrounded by decomposed waste. The exposure pathways are similar to those for the well-drilling scenario: inhalation of dust and volatile chemicals during excavation, external exposure to radiation or dermal exposure, and incidental ingestion of contaminated soil.

SCENARIO PARAMETER SELECTIONS

For this example, the input parameters and assumptions for each exposure pathway and scenario are selected to provide a reasonable estimate of the likely radiation dose to an average individual in a population. In general, the parameter values were 1) selected directly from the literature 2) selected to be consistent with literature values (such as those published by the ICRP), or 3) selected because they were standard default values for assessments at the Hanford Site. A listing of the major parameters or assumptions for the well-drilling and

excavation scenarios, their expected ranges, and the values selected for this sample demonstration are given in Tables I and II. An attempt was made to select values well within the expected range, rather than at the extremes of the expected range.

SOURCE TERM

Nine radionuclides potentially found in a mixed-waste disposal facility were selected for this study. These radionuclides represent a wide range of radiological properties and can be organized into the following four radionuclide groups:

(a) alpha emitters (^{238}U, ^{239}Pu and ^{241}Am)

(b) high- to moderate-energy photon emitters (^{60}Co and ^{137}Cs)

(c) low-energy photon emitters (^{129}I)

(d) non-photon emitters (^{90}Sr, ^{63}Ni, and ^{99}Tc).

The example calculations in this paper are based on an activity of 1 mCi per m^3 (1600 kg of soil plus waste) for each radionuclide contained in buried waste. The equivalent concentration in mass units (mg of the isotope per kg soil) are listed in Table III.

Three chemical constituents were chosen to represent potential chemical carcinogens: 1,1,2 trichloroethane (112 TCA), acetonitrile, and PCBs (mixed arochlors). The results presented in this paper for chemical constituents are based on unit concentrations, 1 mg/kg, of waste disposed.

TABLE I. Expected Ranges of Pathway Parameters for Water-Well Drilling Scenario

Pathway Parameter	Expected Range	Selected Values	Comments
Inhalation (particulates)			
Duration (h)	0 to 40	1	Waste drilling
		40	Overall operations
Breathing rate (cm^3/s)	125 to 333	270	GENII default value[4]
Concentration (g/m^3)	10^{-6} to 10^{-2}	10^{-4}	Waste drilling
Particle size (μm AMAD)[a]	0.1 to 10	1.0	ICRP default value[5]
Inhalation (volatile)			
Duration (h)	0 to 40	40	Overall operations
Volatilization rate	chemical-dependent		Method from RAPS/MEPAS[6]
Dispersion factor (s/m^3)	10^{-4} to 1	0.01	
External			
Duration (h)	0 to 40	40	Overall operations
Dermal			
Exposure events (total)	0 to 5	5	Once each day
Area exposed (m^2)	0 to 1.75	0.2	Forearms and hands
Skin loading (mg/cm^2)	1 to 3	2	EPA value[2] Literature value[7]
Fraction absorbed	0 to 1	0.03[b]	
Ingestion (soil)			
Quantity (mg/d)	0 to 480	300	Outdoor activity
Soil surface concentration (mg/kg)	0 to 1	2.3×10^{-2}	To a depth of 15 cm

(a) Where AMAD means the "activity mean aerodynamic diameter" of the airborne particulate material.

(b) Chemical-dependent: however absorbed, the fraction estimated for the three compounds is the same based on graphs in McKone 1990 (fig. 3-6).[7] The figures give the fraction for 12-hour exposure as a function of soil-loading on skin for different values of octanol/water partition coefficient (K_{ow}) and the constant (K_h) from Henry's law.

TABLE II. Expected Ranges of Pathway Parameters for the Excavation Scenario

Pathway Parameter	Expected Range	Selected Values	Comments
Inhalation			
Duration (h)	0 to 100	80	Two work-weeks
Breathing rate (cm^3/s)	125 to 333	270	GENII default value[4]
Concentration (g/m^3)	10^{-6} to 10^{-2}	$5x10^{-3}$	TLV, respirable dust
Particle size (μm AMAD)[a]	0.1 to 10	1.0	ICRP default value[5]
Inhalation (volatile)			
Duration (h)	0 to 100	80	Overall operations
Volatilization rate	chemical-dependent		Method from RAPS/MEPAS[6]
Dispersion factor (s/m^3)	10^{-4} to 1	$2.5x10^{-3}$	
External			
Duration (h)	0 to 100	80	Two work-weeks
Dermal			
Exposure events (total)	0 to 10	10	Once each day
Area exposed (m^2)	0 to 1.75	0.32	Forearms, hands, head
Skin loading (mg/cm^2)	1 to 3	2	EPA value[2] Literature value[7]
Fraction absorbed	0 to 1	0.03[b]	
Ingestion (soil)			
Quantity (mg/d)	0 to 480	300	Outdoor activity
Soil surface (mg/kg)	0 to 1	1	Clean overburden

(a) Where AMAD means the "activity mean aerodynamic diameter" of the airborne particulate material.

(b) Chemical-dependent: however absorbed, the fraction estimated for the three compounds is the same based on graphs in McKone 1990 (fig. 3-6).[7] The figures give the fraction for 12-hour exposure as a function of soil-loading on skin for different values of octanol/water partition coefficient (K_{ow}) and the constant (K_h) from Henry's law.

TABLE III. Radionuclide Source Term, Grouped by Characteristics

Radionuclide	Halflife (yr)	Specific Activity (Ci/g)	Concentration (mg/kg) Equivalent to 1 mCi/m^3
^{236}U	4.5E+09	3.4E-07	1.9E+03
^{239}Pu	2.4E+04	6.2E-02	1.0E-02
^{241}Am	4.3E+02	3.4E+00	1.8E-04
^{60}Co	5.3E+00	1.1E+03	5.5E-07
^{137}Cs	3.0E+01	8.6E+01	7.2E-06
^{129}I	1.6E+07	1.8E-04	3.6E+00
^{90}Sr	2.8E+01	1.4E+02	4.5E-06
^{63}Ni	1.0E+02	5.7E+01	1.1E-05
^{99}Tc	2.1E+05	1.7E-02	3.7E-02

EXPOSURE TO RADIONUCLIDES

Radiation doses for the intruder scenario analysis were calculated using the GENII computer software package and default dosimetry data.[4] GENII calculates doses from acute and chronic exposures to individuals or population groups for inhalation, ingestion, and external exposure pathways. In this paper, the risk from radiation exposure is converted to fatal cancer risk by using a risk factor of 4×10^{-4} per rem as given in ICRP 60 for occupational exposure to radiation.[8]

The results of the radiation dose calculations, summarized in Table IV, are based on intrusion into a site containing 1 mCi/m^3 (assuming 1 m^3 = 1600 kg soil) of each radionuclide. This activity is converted to mass units, mg of the isotope per kg soil, to facilitate comparison with the concentration of chemical constituents.

TABLE IV. Calculated Radiation Dose and Cancer Risk to Individuals, Ranked by Risk, Assuming Exposure to a Buried Waste Concentration of 1 mCi/m^3

Scenario Nuclide	Dose by Pathway (rem) Ingestion	Inhalation	External	Total	Risk of Fatal Cancer[a]
Drilling					
^{60}Co	1.2E-06	1.6E-09	2.6E-03	2.6E-03	1E-06
^{137}Cs	5.7E-06	2.3E-10	6.2E-04	6.3E-04	3E-07
^{241}Am	4.4E-04	3.5E-06	4.7E-06	4.5E-04	2E-07
^{129}I	3.0E-05	1.2E-09	1.8E-06	3.2E-05	1E-08
^{90}Sr	1.5E-05	1.6E-09	1.2E-07	1.5E-05	6E-09
^{239}Pu	6.0E-06	2.4E-06	4.6E-08	8.4E-06	3E-09
^{238}U	2.8E-06	9.2E-07	2.8E-08	3.7E-06	2E-09
^{99}Tc	2.7E-07	6.7E-11	1.7E-08	2.9E-07	1E-10
^{63}Ni	6.6E-08	1.7E-11	6.3E-11	6.6E-08	3E-11
Excavation					
^{241}Am	5.4E-03	8.4E-02	1.0E-04	8.9E-02	4E-05
^{60}CO	1.5E-05	3.8E-05	5.8E-02	5.8E-02	2E-05
^{239}Pu	7.5E-05	5.8E-02	1.0E-06	5.8E-02	2E-05
^{238}U	3.5E-05	2.2E-02	6.3E-07	2.2E-02	9E-06
^{137}Cs	7.1E-05	5.7E-06	1.4E-02	1.4E-02	6E-06
^{129}I	3.7E-04	2.9E-05	4.1E-05	4.4E-04	2E-07
^{90}Sr	1.8E-04	3.9E-05	2.6E-06	2.2E-04	9E-08
^{99}Tc	3.3E-06	1.6E-06	3.7E-07	5.3E-06	2E-09
^{63}Ni	8.3E-07	4.2E-07	1.4E-09	1.3E-06	5E-10

(a) Risk for workers, as given in ICRP Publication 60, is based on the conversion factor 4 x 10^{-4} fatal cancers per rem.

EXPOSURE TO HAZARDOUS CHEMICALS

The intruder scenarios developed for non-radioactive contaminants were consistent with those used for radioactive contaminants. The hazard assessment for non-radioactive materials was performed using guidance from the EPA.[2] Calculations were made using simple chronic

exposure models similar to those in the GENII software system and the Multimedia Environmental Pollutant Assessment System (RAPS/MEPAS).[4][6] A database was created to store parameter values, perform the calculations, and create reports. Exposures to hazardous chemicals by inhalation, ingestion, and dermal contact were estimated. The potential consequences for intruder scenarios are reported as cancer risk for carcinogenic chemicals.

Risks from exposure to carcinogens are based on Cancer Potency Factors (CPF), referred to as slope factors.[2] The CPF, in units of kg-d/mg, multiplied by a chronic intake rate, in units of mg/kg/d, gives the incremental probability of an individual's developing cancer as a result of a lifetime exposure to a carcinogen. Because the CPF (slope factor) is an upper confidence limit (95th percentile) of the probability of response, the carcinogenic risk estimate will generally be an upper-bound estimate.[2]

Table V shows the subset of chemicals chosen for analysis, and the cancer potency factors associated with each constituent. Most of the data on chemical properties and toxicity were taken from a document written for the Multimedia Environmental Pollutant Assessment System (MEPAS).[9] The calculations are based on a buried waste concentration of 1 mg/kg (1 ppm) of each constituent in soil.

Table VI lists cancer risks by pathway and constituent for each scenario. These are lifetime risks, based on one exposure event for the individual well-driller or excavator. For the assumptions chosen for the scenarios, the dermal absorption pathway dominates the risk from

TABLE V. Cancer Potency Factors for Selected Carcinogens
Cancer Potency Factor

Constituent	Cancer Potency Factor (kg-d/mg) Inhalation	Ingestion
112 TCA	5.7E-02	5.7E-02
Acetonitrile	3.6E-02	3.6E-02
PCB	6.1E+00	1.2E+01

TABLE VI. Calculated Risk of Fatal Cancer by Pathway and Chemical Constituent

Scenario Constituent	Cancer Risk, by Pathway[a] Ingestion	Inhalation	Dermal	Total Risk
Drilling				
PCB	4E-10	8E-15	3E-08	3E-08
112 TCA	1E-12	4E-14	1E-10	1E-10
Acetonitrile	1E-12	2E-14	9E-11	9E-11
Excavation				
PCB	3E-08	3E-10	5E-06	5E-06
112 TCA	9E-11	2E-12	1E-08	1E-08
Acetonitrile	7E-11	4E-13	1E-08	1E-08

(a) Lifetime risk based on one exposure event.

these chemicals. Dermal absorption was estimated from McKone 1990 Fig. 3-6: taken as 0.03 for the chemicals evaluated here.[8]

EXAMPLE RISKS FROM RADIONUCLIDES AND CARCINOGENIC CHEMICALS

The cancer risk from radionuclides and carcinogenic chemicals for the example scenarios are given in Table VII. These results are based on the exposure assumptions for the well-drilling and excavation scenarios. The values for cancer risk are listed in the order of

TABLE VII. Calculated Potential Risks (with no protective measures) for the Well Drilling and Excavation Scenarios

Scenario Constituent	Radionuclides Risk per 1 mCi/m^3	Radionuclides Risk per 1 μg/kg	Chemicals Risk per 1 mg/kg
Well Driller			
^{60}Co	1E-06	2E-03	-[a]
^{137}Cs	3E-07	3E-05	-
^{241}Am	2E-07	1E-06	-
^{129}I	1E-08	4E-12	-
^{90}Sr	6E-09	1E-06	-
^{239}Pu	3E-09	3E-10	-
^{238}U	2E-09	8E-15	-
^{99}Tc	1E-10	3E-12	-
^{63}Ni	3E-11	2E-09	-
PCB	-	-	3E-08
112 TCA	-	-	1E-10
Acetonitrile	-	-	9E-11
Excavator			
^{241}Am	4E-05	2E-04	-
^{60}Co	2E-05	4E-02[b]	-
^{239}Pu	2E-05	2E-06	-
^{238}U	9E-06	5E-12	-
^{237}Cs	6E-06	8E-04	-
^{129}I	2E-07	5E-11	-
^{90}Sr	9E-08	2E-05	-
^{99}Tc	2E-09	6E-11	-
^{63}Ni	5E-10	5E-08	-
PCB		-	-5E-06
112 TCA	-	-	1E-08
Acetonitrile	-	-	1E-08

(a) A dash indicates that the calculation is not appropriate for the constituent shown.
(b) Risk value not applicable for high dose rate.

highest to lowest risk, based either on 1 mCi/m3 of each radionuclide or on 1 mg/kg of each chemical constituent. Consistent with guidelines promulgated by the EPA for presenting results, no attempt has been made to combine the risks from radionuclides and chemicals for this example.

DISCUSSION

Analysis of risks using hypothetical scenarios is standard practice for performance assessment for low-level radioactive waste disposal. In this paper, the example scenario analysis considers "worst case" consequences of human intrusion through drilling or excavating into waste because it is assumed that no protective measures would be taken. Such protective measures could include markers or barriers to prohibit intrusion or the use of protective clothing or respirators to lessen the exposure when hazardous materials are encountered. The example methods described in this paper should be applicable to short-term exposures to carcinogenic chemicals because the absorbed dose is the parameter of interest--regardless of the duration of the intake period.

The greatest sources of uncertainty in making risk estimates are the likelihood of the scenarios and the validity of the data and assumptions (i.e., how well the conceptual model of the situation fits reality). For the example scenarios, one of the most uncertain areas is the method for estimating risks from dermal absorption for carcinogenic chemicals. Potential errors include both the absorption values for each chemical and the modeling assumptions associated with skin loading and contact time. For the simple examples in this paper, not all of the

exposure pathways for radionuclides and chemicals have been treated in the same manner. For example, dermal absorption of radioactive materials and the dose from radioactive materials on the skin have not been accounted for in a manner parallel to the way in which dermal exposure to chemicals was calculated.

Applying these scenarios to an occupational setting may provide an upper bound on the risk of one exposure event because protective clothing and control of contamination through control zones will likely reduce exposures. If respiratory and dermal protection for workers are used, a reduction of chemical exposures by a factor of more than 1000 may be attainable. External radiation exposures could also be reduced by controlling the time spent in potentially contaminated areas. Certain types of occupational exposures, including those of workers who may spend an extended amount of time performing site characterization or remediation work, might incur higher risks than those estimated for this paper. Full-time work in a situation similar to the scenarios described would result in an annual exposure duration 25 to 50 times the values for a single event. However, the exposure assumptions for the scenarios are conservative, and therefore do give a likely upper bound for the potential risk from single exposures to radionuclides and hazardous chemicals in an occupational setting.

ACKNOWLEDGMENT

Pacific Northwest Laboratory is operated for the U.S. Department of Energy by Battelle Memorial Institute under Contract DE-AC06-76RLO 1830.

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